$\times 10^{15}$ cm^{-3} at $t = 2$ μsec along a line at $R = 5$ cm (assuming a 30-cm path length). Electron temperature measurements, by ruby-laser Thomson scattering, give 30 eV at the same space-time point. If we define β as the particle pressure on the magnetic axis divided by the externally applied magnetic pressure we find $\beta = 0.4$ at $t = 2$ μsec.

Finally, we have observed the radial profile of the electron density at late times. We see that the toroidal plasma has remained intact for 30 μsec, corresponding to ~ 40 Alfvén transit times from the end of the coil to the center. At this time the density has dropped to about half its initial value. No evidence of gross instability is seen.

In summary, we have observed the formation of a toroidal magnetic configuration with closed surfaces formed by a pinch-implosion technique. Toroidal and poloidal magnetic fields as well as ion temperatures have been measured. In the future we plan to install the necessary circuitry to prolong the B_z field and to study lifetimes on the magnetohydrodynamic and diffusion timescales.

We gratefully acknowledge the technical assistance of K. R. Diller in constructing the experiment. This work was supported by the U. S. Department of Energy under Contract No. DE-AC05-77ET-53044.

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Ordinary-Mode Fundamental Electron-Cyclotron Resonance Absorption and Emission in the Princeton Large Torus

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Fundamental electron-cyclotron resonance damping for 4-mm waves with ordinary polarization as well as blackbody emission is measured along the midplane of the plasma in the Princeton Large Torus. Optical depths obtained from the data are in good agreement with those predicted by hot-plasma theory. The use of ordinary-mode fundamental electron-cyclotron resonance heating in existing and future toroidal devices is supported by these results.

In fusion research there is considerable interest in understanding and utilizing wave absorption and emission near the electron-cyclotron frequency, f_{ce}, and its harmonics.[1] In the Model-C Stellarator, the extraordinary-mode absorption measurements near $2f_{ce}$ were successfully used, not only to measure T_e but also to study the details of the electron velocity distribution function.[2] However, the recent development of powerful millimeter microwave sources (i.e., gyratrons) has stimulated considerable interest in wave absorption near f_{ce} since a clear understanding of the absorption process can prescribe the proper conditions for efficient application of electron-cyclotron resonance (ECR) heating in tokamaks. The primary schemes for ECR heating of tokamak plasmas are (1) as a general method of heating the bulk electrons, and (2) as a specific method of controlling the T_e profile with spatially localized heating with beneficial conse-

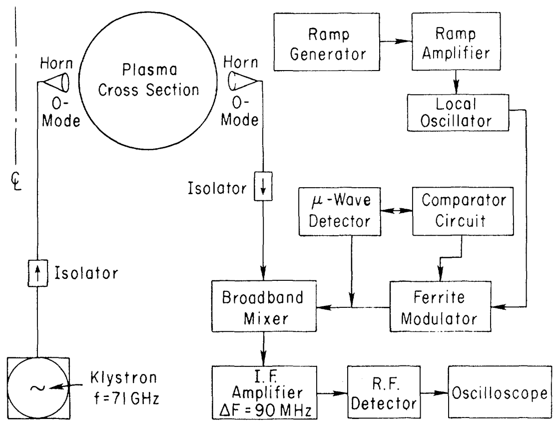

FIG. 1. Block diagram of the experimental arrangement.

quences including, for example, the suppression of magnetohydrodynamic (MHD) instabilities. For ECR heating of tokamaks the attractive feature of the f_{ce} ordinary mode is that the wave can be launched from the low-magnetic field side of the torus, but the ordinary mode has a critical density half that of the extraordinary mode.

In this Letter, we present the first direct measurements of f_{ce} ordinary-mode wave absorption, along with the corresponding emission scans over the midplane of a hot tokamak plasma in the Princeton Large Torus (PLT). These measurements are found to be in good agreement with the predictions of the relativistic hot-plasma theory of Fidone, Granata, Ramponi, and Meyer[3] as well as the full-wave absorption calculations of Antonsen and Manheimer.[4] We then present the experimental evidence which demonstrates that in PLT discharges, with a sufficiently low runaway population, the ordinary-mode emission near f_{ce}, when viewed from the outside of the torus, is essentially at the blackbody level.

Figure 1 is a schematic block diagram of the experimental arrangement. The incident 4-mm microwave power, P_0, is supplied by a klystron transmitter at a fixed frequency of 71 GHz. The orientations of both the transmitter and the receiver horns are such that their electric vectors, $\vec{E}$, are parallel to $\vec{B}$ and their axes are perpendicular to $\vec{B}$. The microwave power transmitted through the PLT plasma is collected by the receiver horn and is mixed with a fixed amount of reference signal from a local oscillator. The resultant rf output is amplified (by an amplifier of bandwidth $\Delta f \approx 90$ MHz) and is then detected with an rf detector. The signal from the output of the detector, displayed on an oscilloscope is proportional to the transmitted power, P_T. The local oscillator is swept, repetitively, from 70 to 72 GHz in 10 msec. With this sweeping technique any small frequency drifts of the transmitter relative to the local oscillator do not affect the absorption measurements, and the frequency-integrated absorption over the f_{ce} resonance is obtained for a direct comparison with the predictions of the relativistic hot-plasma theory of Refs. 3 and 4. Finally, both the transmitter and the local oscillator power are stabilized by self-contained power-leveling feedback loops (Hughes 44764 H), described elsewhere.[5] For emission measurements we turn off the transmitter klystron and increase the amplifier bandwidth to $\Delta f = 400$ MHz. Then, radial profiles of $T_e(r)$ are obtained by repetitively sweeping the local oscillator from 60 to 90 GHz in 10 msec throughout the duration of the discharge.

The fractional microwave power (P_T/P_0) transmitted through the plasma may be written $(P_T/P_0) = \exp(-\tau)$, where $\tau = \int_{R_0-a}^{R_0+a} 2\,\mathrm{Im}(k_\perp)\, dr$ is the optical depth, P_0 and P_T are the incident and transmitted powers, respectively, Im signifies the imaginary part, $a = 40$ cm is the minor radius of the plasma, $R = R_0 + r$, $R_0 = 132$ cm being the nominal major radius at the center of the PLT plasma. According to the relativistic hot-plasma theories of Fidone *et al.*[3] and Antonsen and Manheimer,[4] the expression for the optical depth appropriate for perpendicular propagation of the ordinary-mode radiation of frequency $f \approx f_{ce}$ may be written

$$\tau \approx \frac{\pi^2 R}{c} \frac{f_{pe}^{\,2}}{f_{ce}} \left(1 - \frac{f_{pe}^{\,2}}{f_{ce}^{\,2}}\right)^{1/2} \left(\frac{\kappa T_e}{m_e c^2}\right), \tag{1}$$

where f_{pe} is the electron plasma frequency, κ is the Boltzmann constant, m_e is the rest mass of the electron, and c is the velocity of light.

Since in tokamaks $B \propto R^{-1}$, the absorbing cyclotron layer $f \approx f_{ce}(R)$ can be placed at the desired R or r by choosing the appropriate central magnetic field level $B(R_0)$ for the fixed transmitter frequency, $f = 71$ GHz. Laser Thomson-scattering measurements give both the density, $n_e(r)$, and temperature, $T_e(r)$, profiles. Thus by changing $B(R_0)$ we can measure the optical depth $\tau(r) = \tau(n_e(r), T_e(r))$ as a function of r, or equivalently, as a function of pairs of values of n_e and T_e. In Table I we summarize our f_{ce} ordinary-mode absorption results for two different experimental runs. The experimental values of the optical depth, $\tau_{\exp}$, have been obtained from

TABLE I. A comparison of the measured experimental values of the optical depth, τ_{exp}, with the corresponding theoretically calculated values, τ_{th}, for the propagation of f_{ce} ordinary mode [see Eq. (1)]. The data were collected over two separate experimental runs and partitioned in this table.

$B(R_0)$ (kG)	$T_e(r)$ (eV)	$n_e(r)$ (10^{13}cm^{-3})	τ_{th}	τ_{exp}
19.1	160 ± 88	0.384 ± 0.08	0.05 ± 0.03	0
20.2	293 ± 171	0.716 ± 0.246	0.21 ± 0.16	0.09 ± 0.03
21.5	240 ± 14	0.7 ± 0.14	0.14 ± 0.04	0.11 ± 0
23.8	647 ± 35	1.09 ± 0.11	0.57 ± 0.06	0.38 ± 0.05
24.9	900 ± 115	1.32 ± 0.087	0.98 ± 0.16	0.876 ± 0.06
21.5	270 ± 57	1.30 ± 0	0.29 ± 0.06	0.3 ± 0.028
22.6	416 ± 186	0.96 ± 0.23	0.35 ± 0.18	0.33 ± 0.07
24.2	760 ± 57	2.59 ± 0.41	1.43 ± 0.13	1.49 ± 0.15
25.0	850 ± 70	2.7 ± 0.42	1.65 ± 0.30	1.89 ± 0.0

the measured values of (P_T/P_0) and the relation $(P_T/P_0) = \exp(-\tau)$. In P_0, the refraction losses have been experimentally taken into account by measuring the transmitted power for the same central density and density profile for reduced $B(R_0) = 16.8$ kG for which there is no cyclotron layer anywhere in the plasma (i.e., for the range $R_0 - 40 \leq R \leq R_0 + 40$ cm) and thus, $\tau = 0$. For plasma discharges where the absorption is measured, the same density profile is maintained. Typically, the refraction losses are about 50%. At low-magnetic field ($B < 21$ kG), signal loss due to refraction is larger than that due to cyclotron damping and this source of systematic error would tend to result in poorer agreement between experiment and theory. The theoretical values of the optical depth, τ_{th}, have been obtained by use of the measured values of n_e and T_e in Eq. (1). The numbers in Table I are the mean values followed by the standard deviation in the measured values of density, temperature, and τ_{exp} for four successive reproducible plasma discharges. It is apparent from Table I that there is good agreement between theory and experiment for values of τ in the range $0.1 \lesssim \tau \lesssim 2$.

As seen from Eq. (1), for $f_{pe} < f_{ce} = f$, $\tau \propto n_e T_e$. Thus the f_{ce} ordinary-mode propagation studies could be used to determine the local electron pressure, i.e., either local n_e or T_e if one of the quantities is measured separately.

Now we present our results for f_{ce} ordinary-mode emission from the PLT plasma. For our receiver system, the power, P, collected by the receiving antenna is $P = kT_e(r,t)\Delta f(1 - e^{-\tau})$, where $\Delta f \approx 400$ MHz is our receiver bandwith. If $\tau \gg 1$, then the emitting f_{ce} layer is optically thick [in practice $\tau(r) \gtrsim 2$] and yields blackbody emission.

In Fig. 2 we show a comparison of the temperature profiles obtained from ordinary-mode fundamental cyclotron emission if we assume the blackbody conditions (the dashed line) with the corresponding profile obtained from laser Thomson scattering (the solid line). The off-axis peak in the temperature profile is due to the influx of tungsten from the limiters cooling the center. The cyclotron-emission profile, taken along the major radius in the horizontal plane, shows an outward shift of the plasma by about 2 to 3 cm while the Thomson-scattering profile, taken along a vertical chord through the plasma center, does not show this shift. This horizontal shift is attributable to either the expected outward shift of the magnetic field surfaces by the plasma

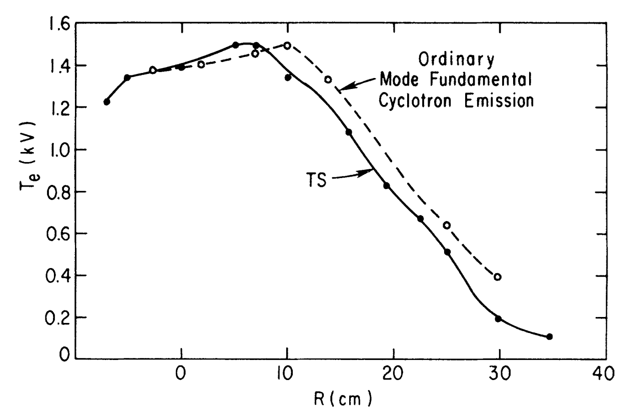

FIG. 2. A comparison of the temperature profiles obtained from blackbody ordinary-mode fundamental cyclotron emission (i.e., the dashed line) with the corresponding profile obtained from laser Thomson scattering, TS (i.e., the solid line).

or to the preprogrammed horizontal positioning of the PLT plasma. Nevertheless, good agreement is found between the two profiles, demonstrating that the emission is near the blackbody level over the range of r shown. The $T_e(R)$ profile has been measured by keeping the receiver at a fixed frequency of 70 GHz and changing the central magnetic field, $B(R_0)$. An absolute calibration of the receiver was achieved with the aid of a noise tube. For the data used in this figure, $n_e(0) \simeq 4 \times 10^{13}$ cm^{-3} and $T_e(0) \simeq 1.4$ keV. Thus, according to Eq. (1), $\tau(0) \simeq 3.2$. Hence, only in the neighborhood of the plasma center is the emitting cyclotron layer optically thick since n_e and T_e are decreasing with r. This indicates that reflections from the vacuum vessel leading to multiple transits of the emitted radiation are enhancing the emission to near the blackbody level for $r > 20$ cm. If b is the wall reflection coefficient, then the effective collected power becomes $P_{\rm eff} \simeq \kappa T_e \Delta f(1-e^{-\tau})/(1-be^{-\tau})$. Even though the measured n_e and T_e at $r = 30$ cm give $\tau \simeq 0.42$, the measured power will be ~90% of the blackbody level for $b \gtrsim 0.95$. Thus, a reflectivity of this level is indicated for the stainless-steel vessel of PLT. Since the acceptance angle of the antenna is rather small ($\lesssim \pm 3°$), only the emission from the vicinity of the spot size of the antenna pattern on the cyclotron layer can reflect from the vessel wall and enter the antenna. Thus multiple reflection will not significantly distort the measured temperature profile.

Taking advantage of this large reflectivity, we measure $T_e(r,t)$ profiles from ordinary-mode cyclotron-emission detection over the outer half of the plasma column by repetitively sweeping the local oscillator frequency from 60 to 90 GHz every 10 msec. In Fig. 3 a three-dimensional computer plot of the time evolution of the electron temperature profile, $T_e(r,t)$, measured for a typical Ohmically heated PLT discharge is given.[6] Such measurements significantly facilitate monitoring $T_e(r,t)$ during a single discharge and are particularly valuable in evaluating effects of auxiliary heating of plasmas.

In conclusion, we have presented the first experimental verification of the predictions of relativistic hot plasma theory (of Refs. 3 and 4) for the propagation of the ordinary mode near the electron-cyclotron frequency in a hot collisionless tokamak plasma. Our absorpiton and emission measurements are in good agreement with Kirchhoff's radiation law when reflections are considered. In PLT, wall reflections play a significant role in enhancing the emission to approximately the blackbody level for $r \gtrsim 20$ cm. Thus, for plasma conditions comparable to those in PLT, ECR heating is quite promising to the extent that these results are applicable to high-rf power levels. Single-pass absorption is essentially total in the plasma core, permitting focusing of the power for heating this region while avoiding loss of power via port leakage. For the conditions studied here, heating the plasma surface requires multipass absorption with inherent leakage, and the power focusing is then influenced by the wave damping profile along the resonance layer. However, heating in the plasma surface will still peak in the horizontal midplane of the plasma and can be confined to a peripheral region. Thus, surface heating to modify the T_e profile, e.g., to stabilize MHD activity[7] should be possible. Of course, higher density and temperature conditions can be employed to provide better localization of the heating in the surface by increasing τ.

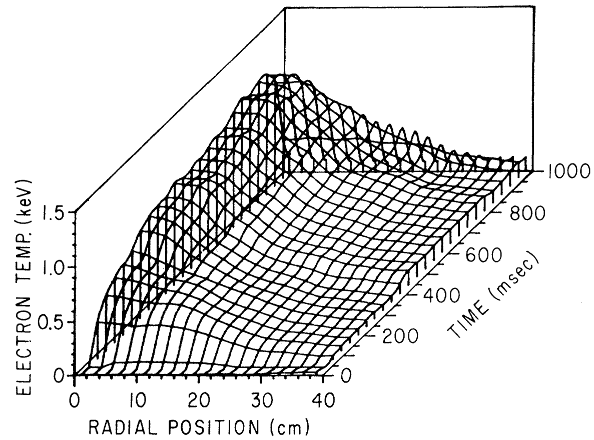

FIG. 3. A computer plot of the time evolution of the electron temperature profile of a typical Ohmically heated PLT plasma discharge determined from the measurement of the ordinary-mode fundamental electron-cyclotron emission by the fast-scanning heterodyne receiver. In order to easily visualize the contours of the three-dimensional graph, only seventeen radial positions of every other temperature profile actually determined from the emission are plotted.

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Measurements of Brillouin-Backscatter Dependence on Density-Scale Lengths near Critical Density

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The Brillouin backscatter fraction was measured from laser-produced spherical plasmas with prepared scale lengths of from 5 to 50 μm. The scale lengths in the region of $0.1 \leq n/n_c \leq 1$ were measured using double-pulse holographic interferometry. The backscatter energy was found to vary from 5% to 25% of the incident energy over the range of scale lengths measured. The spectra of the backscatter light were obtained and show the red shifts characteristic of Brillouin scattering.

Most of the experiments in recent years of laser-plasma interactions with 1.06-μm light have shown rather small (~ 5%) fractions of stimulated Brillouin backscatter.[1] This has been due to the use of very short pulses of less than 100 psec, which lead to short density scale lengths. As the research in the field approaches the longer pulses of greater than 1 nsec, projected to be required for high-thermonuclear-yield experiments, one expects the stimulated Brillouin backscatter will become a serious energy-loss problem. The longer laser pulses can lead to longer density scale lengths in the underdense plasmas, thus creating conditions which are predicted to produce higher fractional stimulated backscatter. We have experimentally simulated these long scale lengths by irradiating spherical targets with a short laser pulse preceded by a controlled prepulse. The density profiles created by the prepulse have been measured by double-pulse holographic interferometry,[2,3] using a fourth harmonic (263 nm) probe beam with $f/2$ collection optics. The energy and spectral distribution of the backscattered light were also measured. We define backscatter as the light which is collected by the focusing lens.

The density region measured was the decade below critical density, i.e., $0.1 \leq n/n_c < 1.0$, where $n_c = 10^{21}$ cm^{-3}. Others[4,5] have examined the relationship between the backscattered energy and the density scale lengths in the more underdense region, near 10^{19} cm^{-3}. Although it was not possible to determine experimentally the density at which the scattering takes place, the following reasoning leads us to believe that Brillouin scattering is most likely to occur near densities of a few tenths of critical density. For a plasma with velocity and density gradients, the convective amplification[6,7] is proportional to $\omega_{pi}^2/(dK/dx)$, where K is the wave-number mismatch due to the gradients. Since these experiments were done on spherical targets, the velocity gradients in the underdense region are much lower than for plane targets, as a result of the divergence. Since the amplification is proportional to ω_{pi}^2, we expect the region of reflection to be at the highest density where modest density gradients exist. Profile steepening[8] may prevent stimulated backscatter from occurring at the highest densities; however, densities less than ~ $0.4n_c$ should be unaffected.[3] (By an analogous process, intense backscatter can self-limit by locally steepening the density profile[9]; this can occur more easily at lower densities.)

These experiments were conducted at intensities of up to 10^{16} W/cm^2, well above the threshold for Brillouin scattering indicated by the linear theory.[6] Therefore, the backscattered wave is expected to grow rapidly until limited by nonlinear effects, such as ion trapping[10] or wave

